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THE EFFECT OF STEADY TORSION ON FATIGUE CRACK INITIATION AND PROPAGATION OF A SIC PARTICLE REINFORCED CAST ALUMINUM MATRIX COMPOSITE

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SUMMARY: Fatigue strength, crack initiation and crack propagation in a SiC_p reinforced cast aluminum composite were investigated. The effect of steady torsion, τ, on alternated tension, $\Delta\sigma$, was also assessed. A comparison of the fatigue and strength properties of the SiC_p composite and an aluminum alloy, similar to the composite matrix, was made.
The materials used in this study were Al-Si-Mg-Cu alloys: a DURALCAN composite (F3S20S), with a 20% SiC particles and an alloy (AS10G) with the same composition of the composite matrix.

KEYWORDS: SiCp metal matrix composite, multiaxial fatigue, steady torsion.

INTRODUCTION

Metal matrix composites (MMCs) are promising materials for structural applications in severe conditions. SiC particles are used to reinforce aluminum alloys.
It's widely accepted that tensile strength, σ_R and σ_c, and Young modulus, E, increase with the introduction of particles or whiskers in an alloy when comparing to conventional matrix materials, [1-3]. On the other hand they usually show relatively poor properties in ductility, ε_R, and fracture toughness, K_{Ic}. On tribologycal properties it's accepted that particles play a very important role increasing enormously wear resistance [1, 4]. It's important to clarify the fatigue properties. Although some authors say that particles increase fatigue strength and crack growth resistance [5], conclusions are still not clear on how particles affect fatigue strength and crack propagation rate [3,6]. For complex stresses results are very few. Real components are usually under complex stresses, and this complex stresses may play a very important role on fatigue behavior. Thus, it's very important to understand how composite materials behave under complex stresses. This work will try to analyze why a steady torsion imposed to an alternated tension changes completely the behavior of the composite.

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MATERIALS AND METHODS

Materials

Chemical composition (wt%) of the materials used in this work are in table 1. As it's observed, they are very similar. Chemical composition (wt%) of SiC particles is listed in table 2.

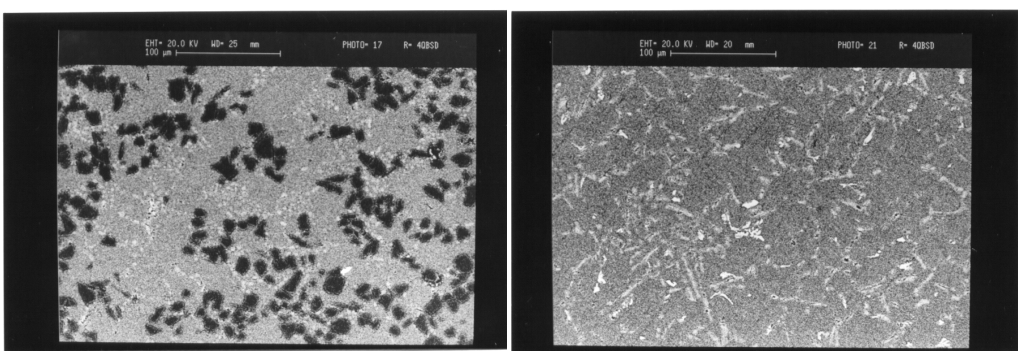
Table 1. – Chemical composition (wt%)

	Cu	**Fe**	**Mn**	**Ni**	**Mg**	**Sn**	**Pb**	**Si**	**Ti**	**Zn**
AS10G	0,10 máx	0,65 máx	0,25 – 0,50	0,05 máx	0,17 – 0,35	0,05 máx	0,05 máx	9,0 – 10,5	0,10 máx	0,10 máx
F3S20S	0,20 máx	0,30 máx			0,75 – 1,20			9,5 – 10,5	0,20 máx	

Table 2. – Chemical composition (wt%) of reinforcement.

SiC	**Free Si**	**Free SiO_2**	**Free C**	**Fe (total)**
98,0 min	0,30 máx	0,50 máx	0,20 máx	0,20 máx

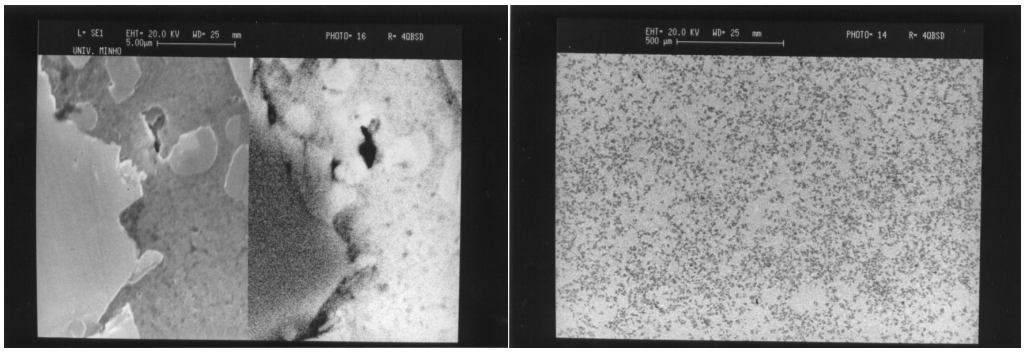
The composite was a 20 ± 2 % SiC_p in volume, and the average size of the particles is 9,3 ± 1,0 μm. Photomicrographs of both the composite and the aluminum alloy are in fig. 1.



a) b)

Fig. 1 – SEM micrographs of microstructure of: a) Composite F3S20S; b) Aluminum (AS10G) alloy.

Fig. 2 shows the good wettability obtained in this material, between the matrix and the reinforcement, and the homogeneous distribution of the particle reinforcement along the specimen length and along the radius.



a) b)

Fig. 2 – SEM micrographs of composite F3S20S: a) Wettability between matrix and reinforcement; b) Distribution along a section of the specimen.

The heat treatment was at 538 ± 10ºC during 8 h followed by water quenching and ageing at 155 ± 10ºC during 6 h for composite F3S20S. And at 540 ± 10ºC during 6 h followed by water quenching and ageing at 160 ± 10ºC during 6 h for aluminum alloy AS10G.

Specimens

Specimens for tension are according to standard DIN-50125; for smooth fatigue tests are in accordance with standard DIN-50113; and for fatigue crack growth behavior, using push-pull tests, specimens are according to ASTM E 606-80 with a pre-crack. Casting of all specimens was made according to ASTM B 108-87.

Methods

Rotatary fatigue tests were conducted at different levels of tension in order to define fatigue strength. Fatigue tests to analyze crack propagation properties were conducted at one level of alternated tension, $\Delta\sigma$, with and without one level of torsion, τ, as indicated in table 4. They were also conducted in laboratory air, ambient air temperature, 20ºC, using a sinusoidal loading, under loading control at a frequency of 8 Hz on a servo-hydraulic testing machine. At each level of tension and torsion the shape of the da/dN-$K_{máx}$ curve was assessed. An assembly allowed to introduce the steady torsion. A Pulsed DCPD system [7] was used to measure the crack growth. Fracture surface examinations were made using an optical microscope and electronic microscope (SEM).

RESULTS

Mechanical properties, (0,2% proof stress, σ_c, tensile strength, σ_r, elongation, ε_r, and Hardness RC) were determined and are in table 3.

Table 3. – Mechanical properties and hardness.

Material	Hardness RC	σ_c(0,2%) (MPa)	σ_r (MPa)	ε_r (%)
F3S20S	108	236,5	265,8	0,25
AS10G	99	145,6	162,1	0,375

The tensile strength and 0,2% proof stress increased in about 64% for the composite while the elongation decreased, when compared with the matrix alloy.

The fatigue strength was investigated using rotatary-bending smooth specimens. Fatigue resistance of the composite is higher for higher stresses while for lower stresses the matrix alloy is a little more resistant (fig.3).

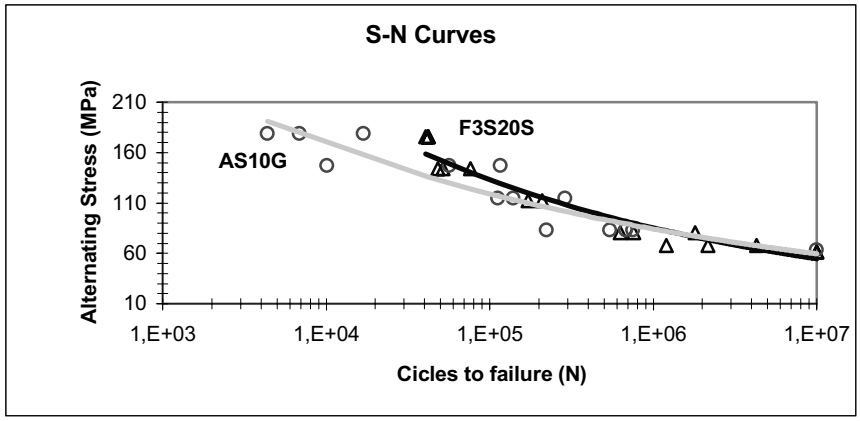


Fig.3 – S-N curves for AS10G alloy and F3S20S vol. 20% SiCp in lab. Air.

Contrarily to the normal fatigue behavior of the dispersion or precipitation strengthened structural alloys, for low cycle fatigue the more ductile showed a lower fatigue resistance while in the high cycle regime (> 1 million) the more strength showed lower resistance. (Fig.3)

Fatigue crack growth behavior was studied using push-pull tests with round specimens according to ASTM E 606-80, with a pre-crack. A comparison between the matrix alloy and the composite was made for crack initiation and crack propagation rates, for high stresses, where the behavior it's different for F3S20S composite and AS10G alloy. The effect of steady torsion was also investigated and compared for both alloys. Fig. 4 shows some results of this tests. The test conditions are in table 4.

Table 4. – Loading conditions for fatigue crack growth behavior.

Loading Conditions	N_f	$\Delta\sigma$ *[MPa]*	τ *[MPa]*	$\sigma^y_{máx}$ *[MPa]*	σ_1 *[MPa]*
		AS10G			
Without torsion	89.596	88,4	0	88,4	88,4
With Torsion	101.189	88,4	87,5	88,4	142,3
		F3S20S			
Without torsion	370.440	88,4	0	88,4	88,4
With Torsion	150.960	88,4	87,5	88,4	142,3

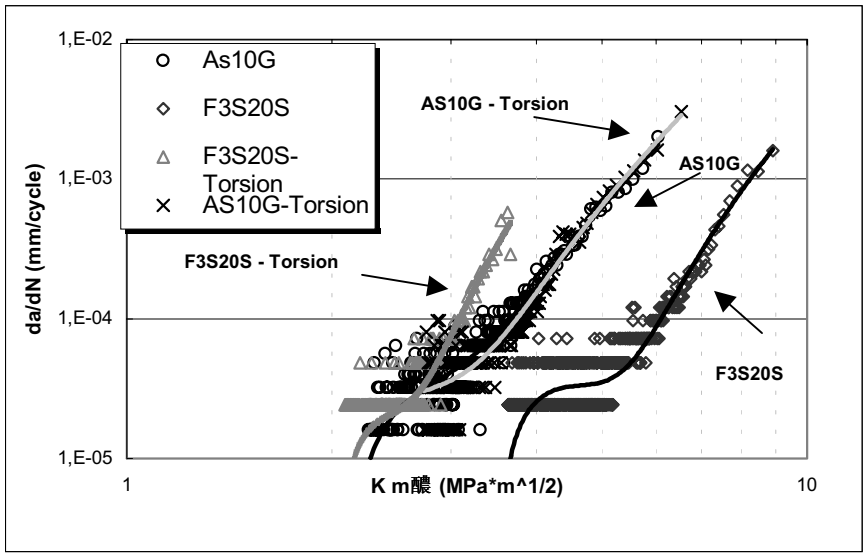


Fig.4 – *da-dN/K_{max}* curves for AS10G alloy and F3S20S vol. 20% SiCp in lab. Air.

The results can be summarized as follows:

1. For the aluminum alloy, AS10G, there's not a significant difference on crack propagation rate, for tests with steady torsion and without steady torsion;
2. For the aluminum alloy, AS10G, steady torsion seems to increase fatigue threshold K_{th}.
3. For the composite alloy, F3S20S, crack propagation without steady torsion is much more resistant when comparing with AS10G;
4. For the composite alloy, when is imposed the steady torsion, crack propagation is much faster than without steady torsion, and than the matrix alloy;

In order to understand the portion of life spent in initiation and in propagation, *a-N/N_f* curves were obtained, and are in fig. 5. In this work it's assumed that initiation life is life until the formation of a 0,5 mm crack. This is only a comparative criterion and doesn't follow any special criterion for it's choice.

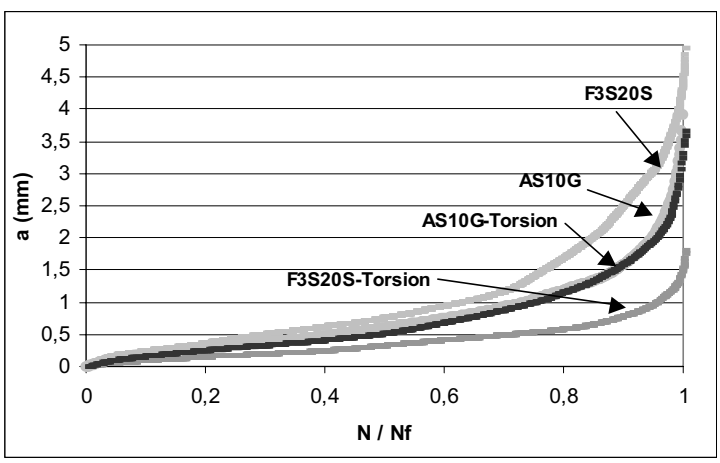
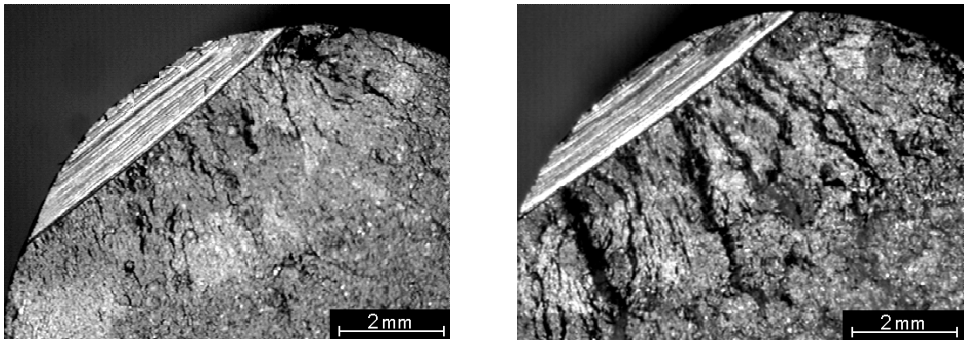


Fig.5 – *a - N/N_f* curves for AS10G without torsion, AS10G with torsion, F3S20S without torsion, and F3S20S with torsion.

The results can be summarized as follows:

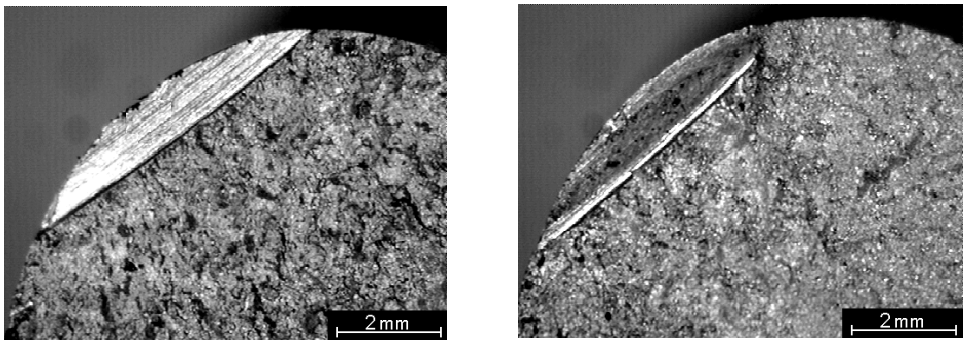
1. For the aluminum alloy, AS10G, there's not a significant difference on initiation life and on propagation life;
2. For the composite, F3S20S, and without steady torsion, it's clear that, although increasing total life, the portion of life (%) spent in initiation decreases. This means that propagation life increases, and resistance to crack propagation increases (see fig.4);
3. For the composite, F3S20S, when it's imposed the steady torsion, initiation life increases significantly, (N/Nf) ≈ 0,7. Propagation life decreases and crack propagation rate increases significantly also (see fig.4).

In order to check crack surfaces, optical microscopic photographs were taken, and are shown on figs. 6 and 7.



a) b)

Fig. 6 – Photographs of fatigue crack fracture morphology of the aluminum alloy AS10G: a) without steady torsion; b) with steady torsion.



a) b)

Fig. 7 – Photographs of fatigue crack fracture morphology of the composite F3S20S: a) without steady torsion; b) with steady torsion.

It's observed that, without steady torsion, surface roughness is about the same for AS10G alloy and F3S20S composite. When is imposed the steady torsion, the AS10G alloy fracture surface seems to be much more irregular than composite F3S20S.

In order to understand the crack growth mechanism SEM microphotographs were taken and are shown on figs. 8 and 9.

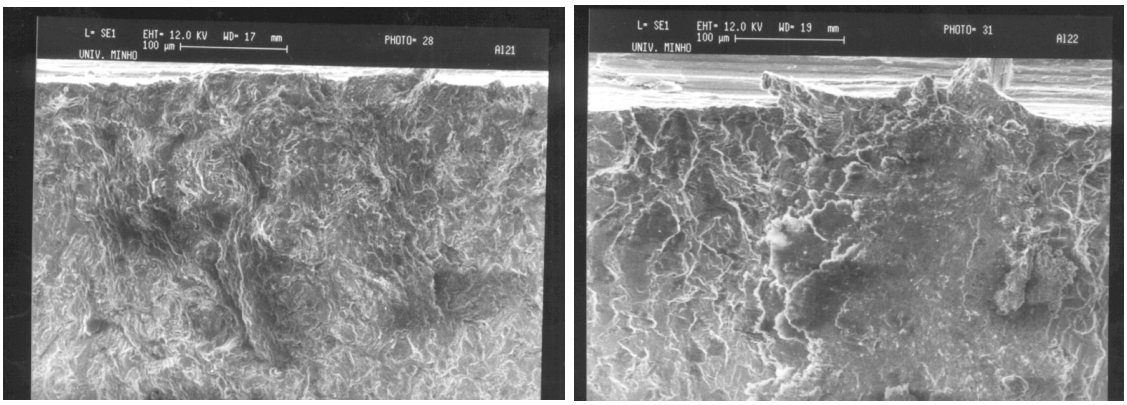


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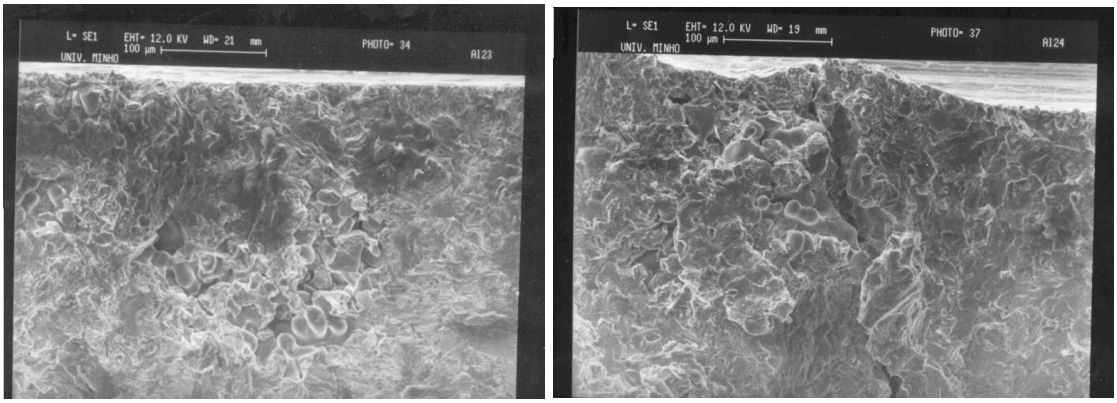
Fig. 8 – SEM microphotographs of fatigue initiation sites of the aluminum alloy AS10G: a) without steady torsion; b) with steady torsion.



a) b)

Fig. 9 – SEM microphotographs of fatigue initiation sites of the composite F3S20S: a) without steady torsion; b) with steady torsion.

It can be seen that crack propagation seems to occur mainly through the matrix on crack initiation. Particles are not broken. It's not clear by the microphotographs that particles act as crack arresters or crack beginners.

DISCUSSIONS

The overall behavior of the composite leads the authors of this work to think that the higher resistance of the composite for higher stresses (fig.3) suggests an intrinsic positive effect of the SiC particles on crack arrest. This positive effect of the reinforcement was confirmed in the crack growth study (fig. 4) with the increasing of the resistance to crack propagation.

By the SEM microphotographs, fig. 9, of different fracture surfaces, it seems that the crack, even at initiation, when high stresses are applied, crosses the particles.

As suggested by Masuda et al [6] the crack mechanism is: for low K_{max}, since the plastic zone is small, the crack keeps away from the particles having a behavior similar to the matrix alloy; for high K_{max}, and bigger plastic zones, the main crack links to the particles and the particles act as

beginners and arresters of the cracks. Observing fig. 3, it's observed that when stresses are low, the composite and the AS10G alloy have the same behavior, because the crack keeps away from the particles. When the stresses are high, the composite is more resistant than the AS10G alloy. This is because the main crack links to the particles and, in our case the particles have an overall behavior as arresters of the cracks. This happens also for crack initiation (< 0,5 mm) and high stresses (fig. 9), where the crack grows faster in the matrix alloy than in the composite although *N/Nf* for the composite is smaller (≅ 0,3) than for the matrix (≅ 0,4) (fig.5).
The effect of steady torsion is quite different for the matrix alloy and for the composite although it reduces total lives for both matrix and composite. In the matrix alloy it's observed that steady torsion doesn't have much influence either in the propagation rate and K_{th} (fig. 4), and propagation life or in the initiation life (fig. 5). On fig. 6 it's observed that steady torsion increases surface roughness. Thus, it would be expected a crack closure effect due to surface roughness, increasing the resistance to crack propagation. Nevertheless it doesn't happen. The answer may be on cyclic properties of this alloy. Since this alloy should soften cyclically, when it's imposed the steady torsion, resistance to crack propagation decreases [8, 9]. Thus this tendency to decrease crack propagation resistance may be compensated by surface roughness effect, which increases crack propagation resistance.
The steady torsion in the composite increases in a large scale the propagation rate and the initiation life (*N/Nf* ≅ 0,7) although the K_{th} doesn't decrease in the same proportion. By optical photographs, (fig.7), it's observed that surface roughness doesn't increase, with steady torsion, as happens with AS10G alloy. By SEM microphotographs, (fig. 9), it's observed that the influence of the particles seems to be the same for specimens with and without steady torsion. On the other hand, the mechanical properties, σ_c, and σ_R, leads us to think that this alloy also softens cyclically. Thus, there is a softening tendency, which is increased due to steady torsion [8,9], decreasing crack propagation resistance. And there isn't a compensating effect, increasing crack propagation resistance, due to surface roughness. As a result, fatigue resistance (fig. 3), and crack propagation resistance (fig. 4), decreases significantly, due to steady torsion. The fatigue threshold also decreases (fig. 4). So, the lower fatigue resistance when it's applied the steady torsion, seems to be related with the matrix properties.

CONCLUSIONS

The main conclusions of this work are as follows:

1. Masuda's theory seems to apply to this work because:
   - At high stresses and high $K_{máx}$, the composite, F3S20S, is more resistant than the matrix alloy, AS10G. Particles have an effect of crack arresters;
   - At low stresses and low $K_{máx}$, the resistance of the composite and of the matrix alloy seems to be the same. Crack propagates through the matrix and particles have no relevant effect;
2. When steady torsion is applied, lower fatigue resistance and crack propagation resistance seems to be related, more with the matrix properties than with the influence of the particles.

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